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Investigation of transients in low-temperature plasmas by means of Particle-In-Cell Modelling

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Background.

Transient perturbations are an effective way to investigate the physical properties of plasmas. Transient phenomena arise through internal instabilities or during sudden changes in external parameters. Here we examine the relaxation of a positive ion (boundary) sheath following a step reduction in the magnitude of the potential across it; the capacitance of the external circuit plays a key role in determining the timescale of the relaxation.

The schematic in Figure 1 shows one practical arrangement that leads to this kind of transient in which a capacitance is discharged by a plasma. Throughout this article the term 'discharge' refers to the neutralization of charge on a capacitor rather than the glowing gas that is often termed 'plasma'. The work is inspired by a related situation in which the external capacitance is initially charged by an RF potential imposed across it and the nonlinear sheath. On sudden termination of the RF the electrical conditions are exactly like those in Figure 1 at the instant of opening the switch. A simple model of the subsequent sheath relaxation [1], based only on conduction currents, is only valid for slow transients. Here, a more complete investigation that includes displacement current is presented.

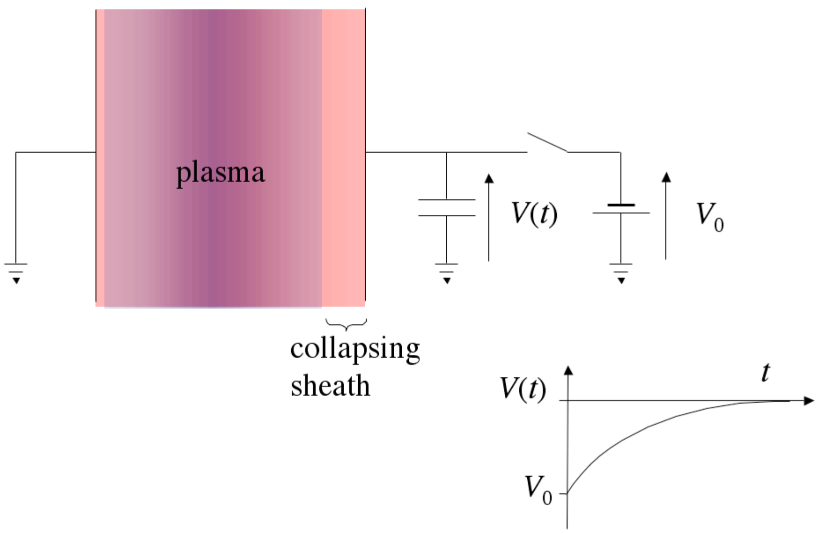


Figure 1 Schematic showing the situation that is being modelled

In the present work, we concentrate on the phase when the sheath collapses, i.e. the time immediately after opening the switch in Figure 1. The simple model [1] equates the difference between the ion and electron fluxes Γ_i and Γ_e, to the rate of arrival of charge on the external capacitor. To follow faster transients the displacement current must be included and that requires modelling of the sheath by analytical or numerical methods.

Including space charge redistribution

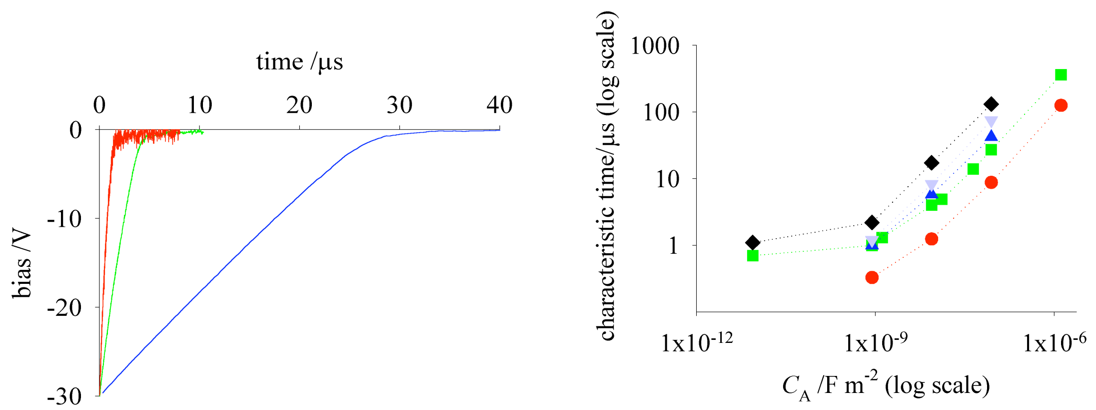
The analytical model has been extended to take account of the redistribution of the electrons as the sheath collapses. It is convenient first to keep the ions fixed (a matrix model); later ion dynamics can be invoked if needs be. The model gives the total current at the electrode surface in terms of particle fluxes and the changing electric field. The displacement current only makes a significant contribution when the external capacitance is comparable with the effective capacitance of the sheath.

A more complete approach would be to model the whole system without seeking to distinguish plasma from sheath. A fluid description based on only two moments of the Boltzmann equation is often amenable to analysis; otherwise it is necessary to solve numerically the full fluid equations, up to the first three moments, closing them with the usual *ad hoc* assumptions. Alternatively, one can follow the evolution of the whole system by means of a kinetic description, with a PIC (Particle-In-Cell) treatment. A PIC model integrates the equations of motion of a very large number of independent 'particles' in their self-consistent electro(magnetic) fields and externally produced forces. Collisions are modelled by means of Monte-Carlo collision method. The PIC/MCC code used in the present work is 1-D, in planar geometry, and was originally devised to describe steady-state situations in RF excited plasmas.

PIC/MCC codes are often employed to find the steady-state plasma configuration, for given external conditions. The initial starting conditions are not critical as the plasma relaxes to its own unique configuration. On the contrary, here we need the follow the relaxation of the plasma, starting from steady initial conditions in which ionization and loss are perfectly balanced. To do this we sustain the plasma by means of an energy input perpendicular to the one dimension in which particle motion is resolved. To establish the initial condition we add, in the dimension analysed, a steady potential difference V_0, which drives an additional DC current across the plasma. At $t = 0$ the voltage source is replaced by a capacitor already holding sufficient charge to make the potential across it equal to V_0. Thereafter the sheath collapses as the plasma discharges the capacitor.

Results

Several simulations have been performed, with initial biases V_0 ranging between 10 and 200 V, with various capacitances C_A, ranging from 8.8 x 10^{-12} to 1.3 x 10^{-6} F/m^2. Figure 2(a) shows how reducing the capacitance speeds the discharge. Figure 2(b) collects results from the full parameter range in terms of a characteristic time *t* which is the intersection with the time axis of the extrapolation of the quasi-linear portion of the discharge. It is apparent that for values of $C_A < 10^{-9}$ F/m^2 the characteristic time no longer scales linearly with the external capacitance but saturates at around 1 μs.



(a) (b)

Figure 2 (a) $V(t)$ for C_A = 8.8x10^{-8}(Blue); 8.8x10^{-9} (Green) and 8.8x10^{-10} (Red) F m^{-2} (b) characteristic times for V_0=10(circle), 30(square), 50(up-triangle), 100(down-triangle) and 200(diamond) V against C_A.

Figure 3 compares the displacement current at the electrode (determined from the time changing electric field) with the current in the external circuit. Together these quantities should account for the particle (conduction) current collected at the electrode. For C > 10^{-8} F/m^2, corresponding to τ >10μsec, the displacement current is indeed negligible and particles arriving at the electrode cause current to flow in the external circuit leading to the discharge of the capacitance. In the experimental work reported in [1] the external current was identified entirely with particle current; the characteristic decay times were of order of a few milliseconds, and the full simulation confirms that the displacement current can indeed be safely neglected under such circumstance.

For C<10^{-9} F/m^2 the particle flow to the electrode is almost entirely committed to changing the surface electric field, i.e. it equates to the displacement current. This leaves little current to flow in the external circuit. Experimentally this regime is virtually inaccessible, as some stray capacitance of the external circuit (from wires etc) is always present, limiting the effective minimum external capacitance achievable.

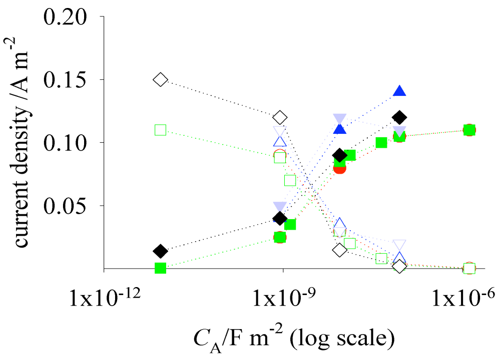


Figure 3 External current (open symbols) and displacement current (closed symbols) at the surface of the RH electrode for V_0=10(circle), 30(square), 50(up-triangle), 100(down-triangle) and 200(diamond) V.

Discussion

The essential physics of the relaxation of a biased plasma has been modelled numerically. The numerical model has been tested by confirming the findings of an analytical model in the case of slow transients. The simulation also shows when and how the simple analytical model [1] fails through its neglect of displacement current.

In this context, it is irrelevant whether the initial bias is set up by means of sheath-rectified RF or DC. Accordingly, the conclusions that can be drawn apply to a range of situations including transients following the changes in RF power for capacitively coupled plasmas as well as the two specific cases cited here of the relaxation of electrostatically confined plasmas that are biased by a DC source or by sheath-rectified RF.

[1] N.St.J.Braithwaite, T E Sheridan and R W Boswell 2003 *J.Phys.D*, **36** 2837-2844